Contract Number DACA42-03-C-0001

ReliOn

FAA Radio Transmit Receive Site Backup Power Demonstration

Final Report

Proton Exchange Membrane (PEM) Fuel Cell Demonstration
Of Domestically Produced PEM Fuel Cells in Military Facilities

US Army Corps of Engineers
Engineer Research and Development Center
Construction Engineering Research Laboratory
Broad Agency Announcement CERL-BAA-FY02

McChord Air Force Base, Washington

June 11, 2004

Executive Summary

On January 14, 2003, ReliOn, then named Avista Labs, installed a 3 kW fuel cell system consisting of six, Independence 500™ fuel cells at McChord Air Force Base in Tacoma, WA. The backup power fuel cell system was located at a Radio Transmit Receive (RTR) site owned and operated by the U.S. Federal Aviation Administration (FAA). Funding for this project was obtained from the Construction Engineering Research Lab, a division of the U.S. Army Engineer Research and Development Center (ERDC). The purpose of the demonstration was to provide reliability data to both the FAA and ERDC to support commercial purchases and installations of the ReliOn Independence fuel cell systems.

The formal commissioning ceremony occurred on April 17, 2003, at which point the one year test program commenced. The six Independence 500™ fuel cells were connected in parallel to the FAA's RTR battery system. These batteries serve as a source of backup power in the event of AC power loss. In this configuration, the fuel cells can significantly extend the backup power run time if called upon. The ultimate run time is limited only by the hydrogen fuel replenishment beyond the nominal 48 kWh storage capacity in the system. The test program was structured in two phases. Phase 1 was scheduled for the first six months of the program, during which the control system simulated a 20 minute loss of AC power three times each day for seven days a week. The fuel cell system automatic start sequence was initiated at the start of each loss of AC power test. For the Phase 1 test runs, the fuel cell power was dissipated in a resistive load bank. Phase 2 took place during the final six months of the program and added a 2 hour grid power failure simulation every Sunday to the daily tests. For this weekly test, the load bank was disconnected and the fuel cells carried the full RTR load while maintaining charge voltage to the facility battery system for the 2 hour period.

The one year test program was completed on Friday, April 17, 2004 and test operations were curtailed on April 19. Through the end of the operating period, the system was monitored for over 8800 hours and accumulated over 1100 successful starts for a total fuel cell run time of 418.9 hours. Total system reliability for the entire test program was 99.4%, reduced only by a faulty hydrogen safety detector, an auxiliary heater failure, and a problem with the onsite laptop computer. This installation and demonstration illustrates the viability of utilizing ReliOn hydrogen-fueled PEM fuel cell systems to supplement and/or replace large lead acid battery systems.

Table of Contents

1.0 Descriptive Title

Demonstration of ReliOn Proton Exchange Membrane (PEM) fuel cells as a backup power system for FAA Radio Transmit Receive communication systems, McChord Air Force Base, Tacoma, Washington.

2.0 Name, Address and Related Company Information

Name:	ReliOn
Address:	15913 E. Euclid Ave., Spokane, Washington 99216
Phone:	509-228-6500
DUNS:	137264193
CAGE:	1G8G7
Federal ID:	91-2191190

ReliOn (formerly Avista Labs) is the leading provider of high reliability fuel cell solutions for backup power applications. The company markets a variety of commercially available Proton Exchange Membrane (PEM) fuel cells using its patented Modular Cartridge Technology.

3.0 Production Capability of the Manufacturer

ReliOn is located in Spokane, Washington and is a provider of commercially available PEM fuel cell systems. Current production consists of Independence 1000™ fuel cell modules and outdoor enclosure systems. These products are manufactured and shipped to industrial, government, and international customers under full commercial warranty programs.

All fuel cell systems are assembled at the Spokane, Washington facility. The current facility has the capability to produce 10 fuel cell systems per week, running one shift and without contract labor. This capacity can easily be expanded with the addition of contract labor and back shifts. If demand exceeds this capacity, the production lines could be duplicated at contract manufacturers. At least three contract manufacturers are available locally which could quadruple the capacity. In addition, large national contract manufacturing firms have been identified to further increase production for even higher demand.

ReliOn fuel cells are made from common materials using mature manufacturing processes in injection-molded plastic, sheet metal fabrication and printed circuit board assembly. The PEM membrane electrode assemblies are purchased through supply agreements with established manufactures. Minor capital expenditures are required to expand production.

4.0 Principal Investigators

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5.0 Authorized Negotiator

Name	Frank Ignazzitto
Title	Vice President, Sales- Government & West
Company	ReliOn
Phone	509.288.6602
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6.0 Past Relevant Performance Information

- Modular 2 kVA Fuel Cell Power Plant with Live Replaceable, Self-Hydrating PEM Smart Cartridges

On November 1, 1998, ReliOn, then named Avista Labs, was awarded a $1,999,786 grant from the Advanced Technology Program of the National Institute of Standards and Technology to further development its novel modular fuel cell power plant design. The project resulted in the successful development, demonstration, and commercial production of modular fuel cell systems with hot-swappable, self-hydrating PEM cartridges. Since the completion of this project, the basic modular fuel cell design has undergone further improvement and now forms the basis of ReliOn's fuel cell product line ranging from 1 kW to 5 kW. Another result of this program was the development of a methanol fuel reformer to produce a hydrogen-rich gas stream for use in the fuel cell systems. Operation of ReliOn cartridges and the fuel cell module was successfully demonstrated in the program.

Company:	U.S. Department of Commerce, National Institute of Standards and Technology, Advanced Technology Program	
Contract Number:	70NANB844069	
Dollar Value:	ATP Cost Share -	$1,999,786
	Avista Labs (ReliOn) Share -	$485,400
	Total Project Value -	$2,485,186
Contact:	Jean-Louis Staudenmann	
Title:	Technical Project Manager	
Phone:	(301) 975-5346	
Date Awarded:	1 November, 1998	

- 242nd Combat Communications Squadron; Geiger Field, WA, Building 401

On March 29, 2002, ReliOn, then named Avista Labs, commissioned a 3kW, SR-72 fuel cell system with funding from the Construction Engineering Research Lab, a division of the U.S. Army Engineer Research and Development Center (ERDC). The purpose of the installation was to demonstrate the viability of PEM fuel cell systems as a reliable source of power to various Department of Defense installations. Additionally, this installation would provide long-term test data of Avista Labs' unique, modular PEM fuel cell system. A major project deliverable dictated the fuel cell provide over 90% availability to its specific customer loads. Specific loads powered included building lighting, building bay doors, and the building Local Area Network (LAN) switch. The system was operational for one year commencing on March 29, 2002 and maintained an uptime of 92.87%.

Company:	U.S. Army Corp of Engineers, Construction Engineering Research Laboratory
Contract Number:	DACA42-02-C-0002
Dollar Value:	$184,300
Contact:	Dr. Mike Binder
Title:	Program Manager
Phone:	(217) 373-7214
E-mail:	m-binder@cecer.army.mil
Project Capacity:	3 kW
Date Installed:	29 March 2002

- SGS Future Installation; Cavalese, Italy

  In November 2002, ReliOn, then named Avista Labs, completed the commercial sale of 13 Independence 1000 fuel cell systems to SGS Future, one of our distribution partners. Ten of these systems were installed in a parallel configuration providing 10kW of power for an installation near Cavalese, Italy. The fuel cells provide power to a mountaintop alpine lodge. Backpackers utilize the lodge, and it was desirable to employ an environmentally clean, quiet, reliable power source. The system has been installed and was operating at the end of 2002. The system was restarted in the spring of 2003. The dollar value below reflects only the cost of the fuel cells. Installation and enclosure costs were paid to a third party contractor by the customer, and not disclosed to Avista Labs.

Company:	SGS Future
Contract Number:	N/A
Dollar Value	$101,226
Contact:	Dr. Andrea Tomasi
Title:	Project Manager
Phone:	+39 (046) 131-4489
E-mail:	tomasi@itc.it
Project Capacity:	10 kW
Date Installed:	15 November 2002

- Independence™ Fuel Cell Shipments

  As of April 2004, ReliOn has shipped a total of 174 PEM fuel cells to customers. Of this total, 86 systems are of the current Independence 1000™ design. This model has been delivered to customers in the following categories:

Universities & Schools	11
Evaluation Testing Agencies	3
Government Applications	35
Other Applications	29
Utility Industry	5
Telecom	3
TOTAL	86

7.0 Host Facility Information

McChord AFB

Don Legg
Phone: (253) 982-2754
Email: don.legg@mcchord.af.mil

FAA

Ernie Sica
Phone: (425) 227-2266
Email: Ernest.Sica@FAA.GOV

Bob McGranahan
Phone: (253) 804-2954
Email: Bob.Mcgranahan@FAA.gov

Dave Powers
Phone: (425) 227-1552
Email: Dave.Powers@FAA.GOV

8.0 Fuel Cell Installation

Figure 1 shows plan view layout of the fuel cell enclosure with integrated hydrogen fuel supply. Photographs of the installation are shown in Figure 2. The outdoor enclosure was located at a distance of 40 feet from the east side of Building 1505 on Outer Drive, McChord Air Force Base, Tacoma, Washington. Building 1505 houses the FAA Radio Transmit Receive (RTR) equipment. The load bank used for Phase 1 simulated load testing was positioned on the east side of the building on a concrete pad. Three conduits extend from the building to the enclosure pad. The conduits carried AC power to the fuel cell enclosure, DC power from the fuel cell enclosure to the load bank and the RTR equipment in the building, control circuits wiring and telephone cables used for data logging and alert notification. A 2/0 AWG ground cable was connected between the facility ground system and the fuel cell enclosure. The composite concrete pad was placed on a bed of compacted gravel. The outdoor enclosure was bolted to the composite concrete pad. Concrete filled bollards were placed around the outdoor enclosure to prevent damage from vehicles. An AC disconnect, DC disconnect and Telephone/Control cable junction box were placed on a distribution back plane near the east side of Bldg. 1505. Two junction boxes were placed on a distribution back plane near the load bank pad for solid state relays and DC connection contactors.

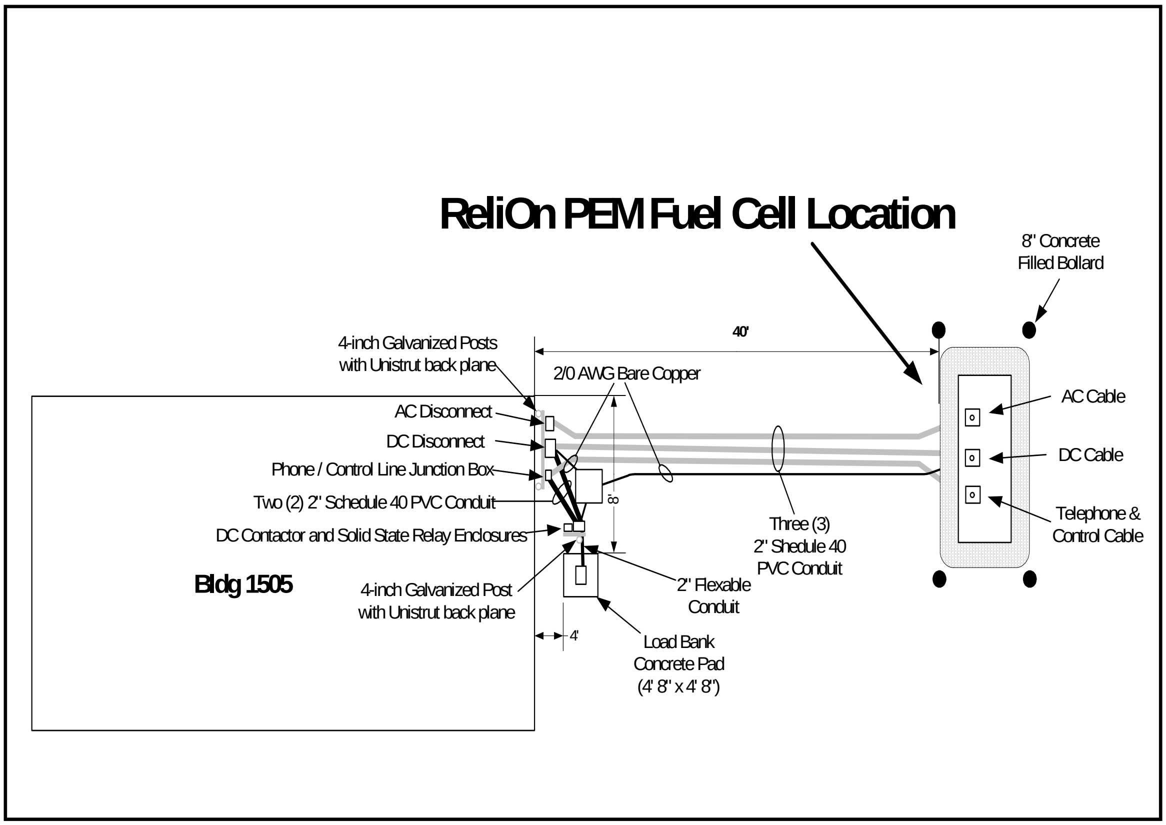


Figure 1. ReliOn PEM Fuel Cell Backup Power System Layout

Figure 2. ReliOn PEM Fuel Cell Backup Power Installation At McChord AFB, Tacoma, Washington

9.0 Electrical System

Figure 3 shows the electrical connection schematic for the fuel cell system. The fuel cells were connected to the internal battery bank through a 150 Amp circuit breaker. The output of the battery bank was then connected to the DC disconnect through another 150 Amp circuit breaker. DC Voltage and current sensors were placed on each side of the internal battery bank to capture the voltage and current out of the fuel cells and the voltage and current out of the system to the load.

The DC disconnect was connected to two contactors that were controlled by a Programmable Logic Controller (PLC 2) located in the control enclosure in the ventilation room of Bldg. 1505. The contactor connecting the fuel cell system to the load bank was normally energized. The contactor connecting the fuel cell system to the FAA battery bank and DC bus was normally de-energized. Another Programmable Logic Controller (PLC 1) in the fuel cell enclosure controlled solid state relays that connected the 1 kW resistive load resisters in the load bank.

During Phase 2 of the system test (described in Section 13), the normally energized contactor was de-energized and the normally de-energized contactor was energized by PLC 2, allowing the fuel cell system to be connected to the FAA DC bus. A blocking diode was used to prevent the FAA DC bus from back feeding the fuel cell system battery bank. A normally closed relay was utilized to simulate power loss to the FAA 24 VDC rectifier. During the simulated power outage the relay opened to remove the AC grid power from the rectifier.

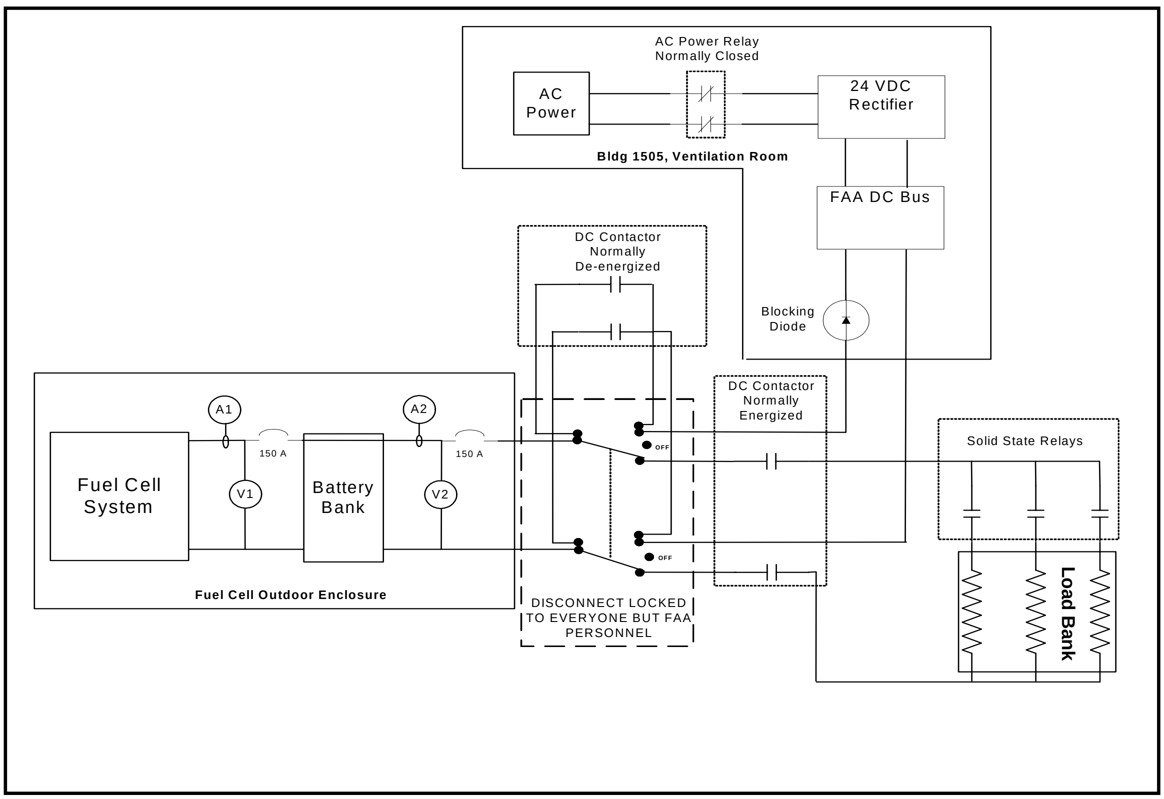


Figure 3. ReliOn PEM Fuel Cell Backup Power Connection To FAA DC Bus And 3 kW Resistive Load Bank

10.0 Thermal Recovery System

Not Applicable

11.0 Data Acquisition System

The data acquisition system is detailed in Figure 4. A data collection unit was connected to various sensors in the fuel cell enclosure. The data collection unit and the fuel cells were each connected to the data-logging computer though an Ethernet hub. The data-logging computer recorded total operating hours of the fuel cells, kilowatt hours produced, fuel consumption, maintenance logs, fuel cell system availability, outages and operating temperature. Additionally, internal and external temperatures and humidities were recorded. The data from the data-logging computer was downloaded to a server located at ReliOn by remote dialup after each scheduled system run. The data-logging computer also recorded alarms for the following conditions: AC power loss, H2 sensor alarm, low power output during test run, system voltage below 24 VDC, fuel cell cartridge off-line and fuel cell shutdown. The data-logging computer alarm notification utility dialed pre-programmed telephone numbers to alert ReliOn of any alarm condition.

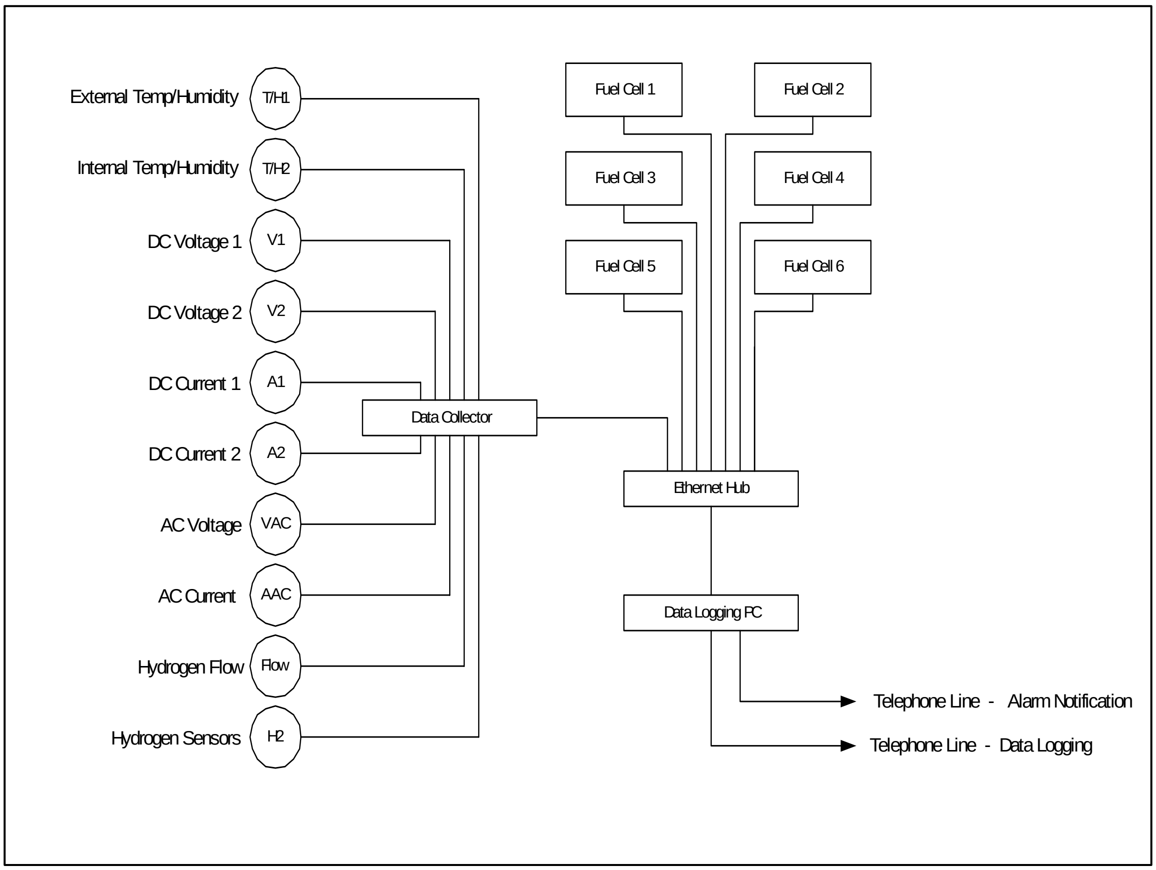


Figure 4. ReliOn PEM Fuel Cell Backup Power Data Acquisition System

12.0 Fuel Supply System

The hydrogen storage and supply system is illustrated in Figure 5. The outdoor enclosure was designed with an integrated hydrogen storage and delivery system. Hydrogen cylinders were contained in cabinets on each side of the enclosure. Each cabinet accommodated three 261 cubic foot cylinders of hydrogen, with a total storage capacity of six cylinders. The hydrogen cylinders were secured in place with nylon straps. Each compartment contained a manifold assembly, pressure regulator, manual shutoff valve, and solenoid valve.

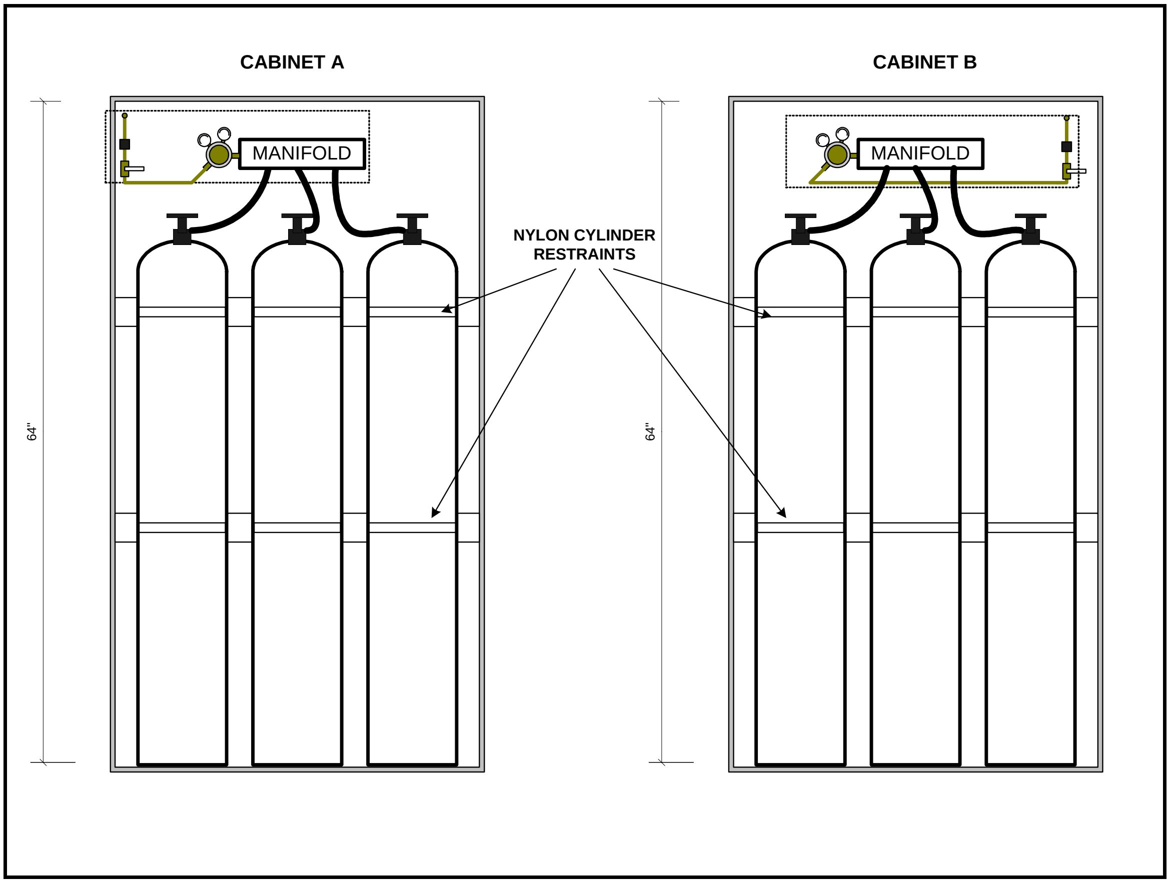


Figure 5. ReliOn PEM Fuel Cell Backup Power Fuel Supply System

The hydrogen supply piping and safety circuit is shown in Figure 6. The hydrogen was piped into the fuel cell cabinets of the enclosure using ¼-inch brass tubing. Prior to distribution to the fuel cells, a flow meter was connected in line to capture the flow rate of the hydrogen. Each fuel cell compartment contained a regulator to regulate the pressure to 5 PSI prior to connection to the fuel cells. The hydrogen bleed from each fuel cell compartment was exhausted though a vent tube on the roof of each compartment. Brushless DC exhaust fans evacuate each fuel cell cabinet for one minute prior to system start. Hydrogen sensors were located in each fuel cell cabinet. The hydrogen supply solenoids were normally closed and interlocked with the normally closed contacts of the sensors. If a leak was detected, the solenoids were de-energized causing them to close. The hydrogen sensor alarm was required to clear before the solenoids were reenergized. A flow orifice limited the maximum possible flow of hydrogen to 2 cubic feet per minute.

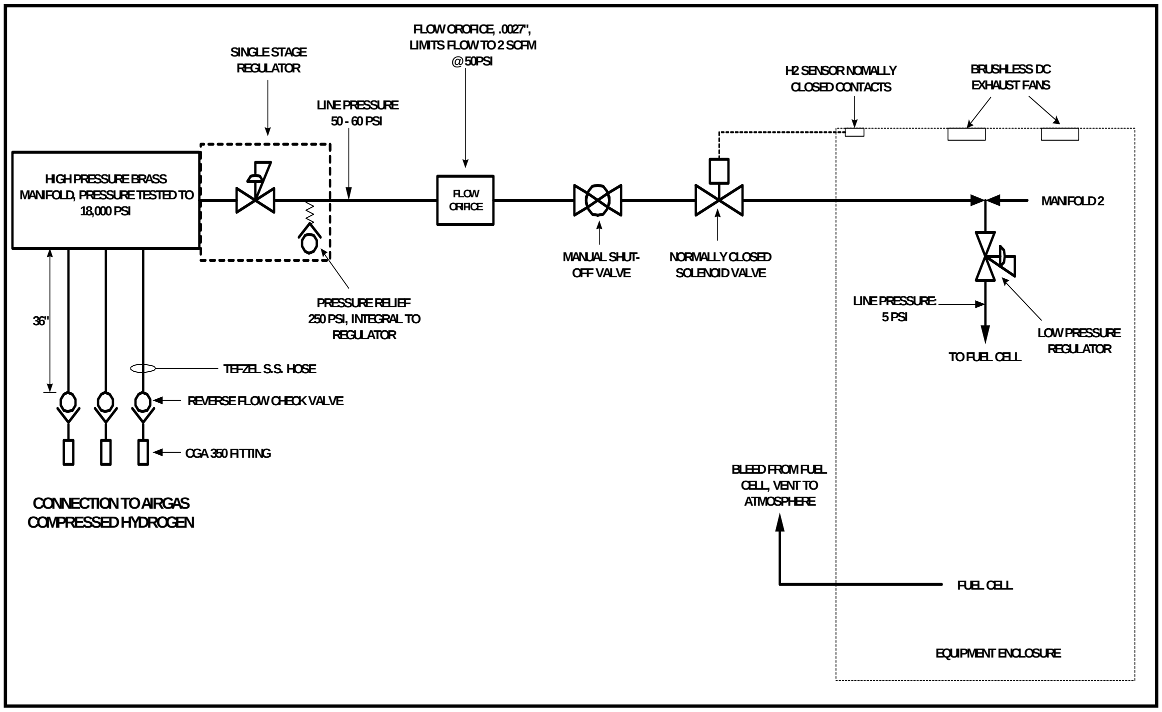


Figure 6. Hydrogen Supply Piping And Safety Circuit

13.0 Fuel Cell Test Program

Figure 7 depicts the system functional block diagram. The system was designed to simulate a typical DC powered system with battery backup. The outdoor enclosure housed the six Independence 500™ fuel cells along with a small internal battery bank, and rectifier. The rectifier and internal battery bank provided power to the PLC controller in the enclosure, data collection system, and data logging computer. AC power was connected to the enclosure to power the rectifier and maintain charge voltage to the internal battery bank when the fuel cells were offline between test periods. AC power was also utilized to power temperature controlled heaters to maintain the temperature inside the enclosure above 4°C (40°F). During the test periods, the PLC in the outdoor enclosure simulated an AC power outage by disconnecting AC from the rectifier and the heaters. At the same time the power outage was simulated, the fuel cell system automatic start sequence was initiated.

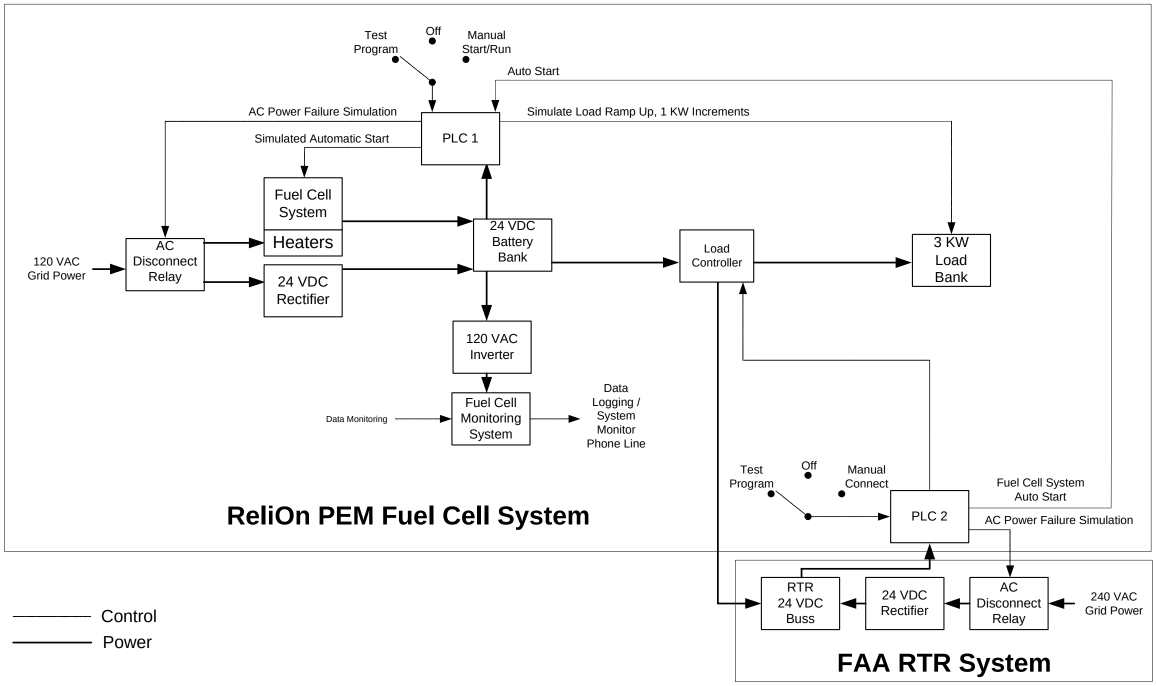


Figure 7. ReliOn PEM Fuel Cell Backup Power Functional Block Diagram

The test program was broken down into two phases:

<u>Phase 1 – Load bank Testing</u>
The first phase involved simulating a 20-minute loss of AC grid power and automatic startup of the fuel call system. A 3kW resistive load bank was then added in 1kW increments during the 20-minute test. The load was increased in 5-minute intervals with the first five minutes at 1 kW, the next five minutes at 2 kW and the final ten minutes at 3kW. The test was conducted three times a day, 7 days a week.

<u>Phase 2 – Radio Transmit Receive (RTR) Site Power</u>
The second phase was started on Sunday October 26, 2003. Phase 2 continued the load bank runs performed in Phase 1, and added a weekly test to provide power to the Federal Aviation Administration (FAA) Radio Transmit Receive (RTR) site for 2 hours every Sunday. The connection to the FAA RTR site involved a simulation of an AC grid power outage at the RTR site, automatic startup of the fuel cell system and automatic connection of the fuel cell system to the RTR site DC bus.

14.0 Program Costs

Table 1 shows a breakdown of project costs for the ReliOn PEM fuel cell backup power demonstration project. The total estimated cost in the proposal budget was $139,973. The total award amount in the fixed-price contract was $136,342. Total billed expenditures (including committed site restoration activities) through April 22, 2004 were $136,342.

Table 1. Project Costs for Contract Number DACA42-03-C-0001

Category	Proposed Budget	Award Amount	Actual Billed Through April 22, 2005
Site Preparation & Installation			
Mechanical & Civil (Consisting of)	$ 22,000		
3 Modular Enclosures for Independence 500s			
Concrete Composite Pad for Enclosure			
Truck Rental for Transport of Skid Mount Enclosure			
Electrical (Consisting of)	$ 12,000		
Install 120 Volt AC Feeder to Enclosure			
Install 48 volt feeder with Disconnects to Customer Load			
Total Site Preparation & Installation:	**$ 34,000**		**$ 34,895**
Fuel Cell & Fuel Storage/Distribution Total:	**$ 34,370**		**$ 28,253**
Monitoring & Communications			
Date Extraction	$ 9,000		
Date Storage	$ 4,000		
Communication	$ 2,000		
Total Monitoring & Communications:	**$ 15,000**		**$ 10,635**
Labor	**$ 28,048**		**$ 38,738**
Fuel Cost	**$ 7,055**		**$ 9,441**
Travel	**$ 16,500**		**$ 7,546**
Miscellaneous			
Replacement or Upgraded Equipment (Consisting of)			
Revised bleed gas system			
Hydrogen sensors			
Total Miscellaneous:	**$ -**		**$ 1,834**
Site Restoration	**$ 5,000**		**$ 5,000**
(Not expended, but committed as of April 22, 2004)			
Project Total:	**$ 139,973**	**$ 136,342**	**$ 136,342**

The cost of industrial grade hydrogen fuel from the vendor was $0.0675 per cubic foot. With handling, delivery charges and taxes, the effective cost of fuel delivered to the site was $0.0858 per cubic foot (not including cylinder rental, charged at $4.50 per cylinder per month).[1] As detailed in Appendix 1, the net fuel cell system efficiency was 56.69% (LHV basis) for the demonstration project. With this system efficiency, the fuel cost rate as consumed was $1.94 /kWh. These costs are illustrated in Figure 8.

[1] In 2003 the fuel charges were $0.156 per cubic foot, and $0.199 per cubic foot as delivered. ReliOn negotiated a new supply agreement with the vendor which took effect on January 1, 2004.

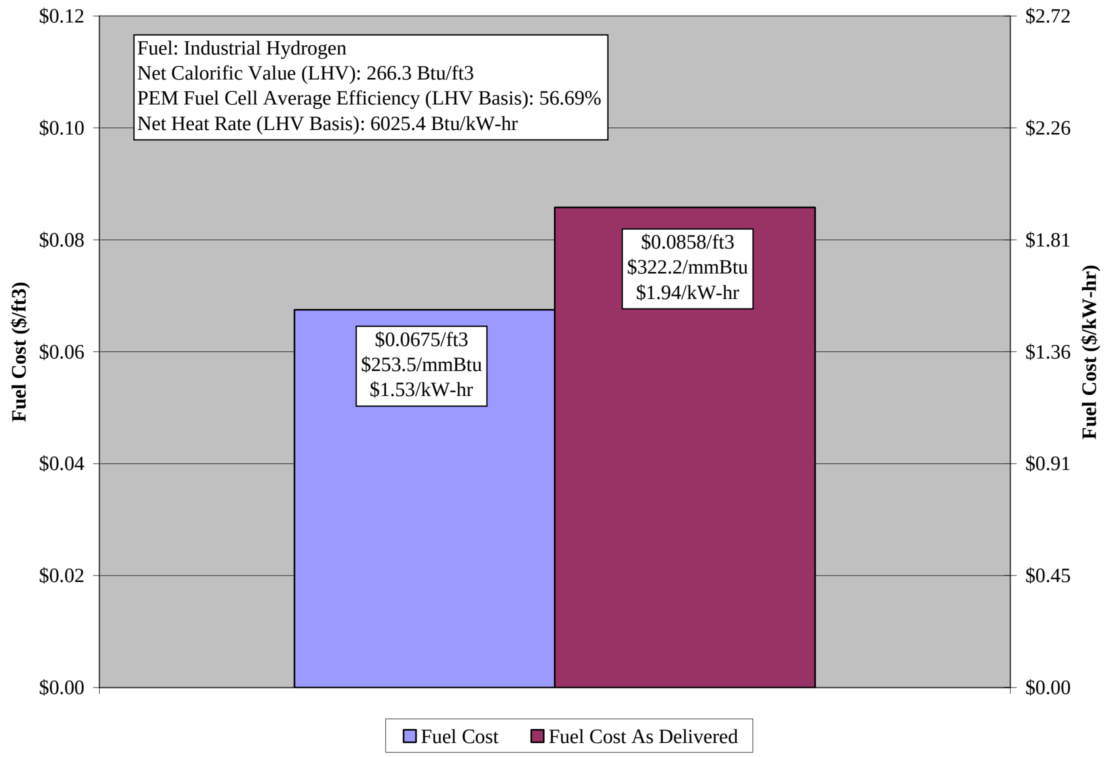


Figure 8. ReliOn PEM Fuel Cell Backup Power Demonstration Project Fuel Costs

15.0 Milestones/Improvements

The one-year test program was completed on Friday, April 17, 2004. The fuel cell systems were shut down following the 4 AM run on Monday, April 19, 2004. Through the end of the operating period on April 19, the total system run time was 418.9 hours, consisting of 410.9 hours of operation within the scheduled test periods, and additional run hours outside of the normally scheduled test periods. The scheduled test runs consisted of 359.6 hours of cumulative Phase 1 data, and 51.3 hours of cumulative Phase 2 data. See Attachment 1 for summaries of run data.

Total reliability (Actual Starts/Attempted Starts) for the entire test program was 99.4%. Total availability (Actual Run Time In Scheduled Period/Scheduled Run Time in Period) for the entire test program was 97.4%. The individual fuel cells were very reliable throughout the 1 year program, presenting an effective demonstration of ReliOn's modular, air cooled, self hydrating, planer technology. Reliability and availability factors of less than 100% are attributed to sub-components, which have since been redesigned to correct the issues. The key events can be summarized as follows:

- June 28 thru July 3, 2003: Overly sensitive hydrogen sensors inside the outdoor enclosure caused several shutdowns during test runs. This was compounded by calibration drift that increased their sensitivity levels further. During the 4 AM run on June 28 the hydrogen sensors forced a complete system shutdown. This event was categorized as an Unscheduled Outage and an unsuccessful start, impacting both availability and reliability totals. Following this run, further operation was curtailed by shutting down the PLC (remotely from Spokane) until onsite service could be performed on July 3. This outage period from the afternoon of June 28 until the morning of July 3 was categorized as a Scheduled Outage. During a scheduled outage period, the fuel cell system was considered to be "not capable of providing service", and the availability total was therefore impacted for the months in which the outages occurred. Since there were no attempted system starts during the scheduled outage, the reliability calculation does not include this period.[2]

To correct the sensor problem, new instruments were installed based on the ReliOn design currently used in the Independence 1000™ fuel cell. There have been no further problems since July 2003. Hydrogen sensors are now designed into ReliOn fuel cell modules and are no longer used inside commercial shipments of the outdoor enclosure.

- July 11, 12, 22: Outages were scheduled through the 4 PM runs on these days to allow onsite service work. This impacted availability, but not reliability.

- October 27 thru 28, 2003: Hydrogen gas vendor did not properly connect gas cylinders. Fuel supply exhausted on October 27. The fuel cell system started for every scheduled test run, but lack of hydrogen forced the system to shut down. Again, this impacted availability, but not reliability.

- December 28 thru 29, 2003: Hydrogen gas vendor missed delivery scheduled for Christmas Eve. Fuel supply exhausted on December 28. The fuel cell system started for every scheduled test run, but lack of hydrogen forced the system to shutdown. Again, this impacted availability, but not reliability.

- December 29, 2003 thru January 2, 2004: Pad heaters applied to the bottom of the fuel cells shorted and tripped the enclosure power breaker. The computer, PLC, and data logger in the enclosure continued running until the batteries were depleted. The system was designed to start from a PLC clock signal and not on loss of AC power. Therefore, the fuel cells did not start. This impacted both availability and reliability. These pad heaters are no longer used in ReliOn outdoor enclosures. They have been replaced by a much more robust design.

Intermittent cracking of the molded plastic outer covers on the fuel cell module cartridges were detected during the test program. To address this issue, a new design of fuel cell cartridge, incorporating a foam aluminum heat sink and aluminum current collectors was installed in one of the modules in January 2004. The installation of this new cartridge type provided additional field service data for the design. Since the beginning of 2004, this new cartridge design has been included with all new Independence 500™ fuel cells delivered to customers. The main benefits of the new aluminum heat sink cartridge design are expanded temperature range, and improved force application. The cartridges were redesigned with an aluminum cover to provide compression force to the MEA. The new aluminum cover cartridges have performed flawlessly through the end of the test program.

[2] Availability and Reliability definitions based on North American Electric Reliability Council, Glossary of Terms, August 1996.

16.0 Decommissioning/Removal/Site Restoration

Upon completion of the successful test program, the FAA requested that the test site be converted to a commercially operating backup power system. This work was completed at the site by ReliOn Application Engineers during the week of June 7, 2004. The conversion effort primarily involved replacement of the six (6) Independence 500™ fuel cells with one (1) current model Independence 1000™ system.

The upgraded system specifications are:

- System Voltage: Nominal 24 VDC
- System Current: 40 Amps
- System Backup Capacity: 48 kWh
- Operating Temperature Range: -40 deg. C to + 46 deg. C

The system was configured to provide the following startup options for a fully functional backup power system for the FAA's RTR site:

- Dry Contact Closure
- Loss of AC power
- Low DC Bus Voltage – user configurable to 22, 23, 24, or 25 VDC trip point

The specific modifications which were undertaken at the McChord RTR site are as follows:

1. Removal of unnecessary test equipment in Outdoor Enclosure
   a. PLC control systems
   b. Independence 500 Communications systems
   c. Leave extra equipment bays for storage space

2. Installation of ReliOn control system in Outdoor Enclosure
   a. Loss of AC Power start relay
   b. Low voltage startup
   c. Startup control box for hydrogen solenoid & ventilation fan

3. Modification of Hydrogen delivery system
   a. Remove fuel cell cabinet regulators
   b. Configure hydrogen delivery system for use with up to two Independence 1000s
   c. Configure hydrogen delivery system to utilize both Hydrogen cabinets
   d. Upgrade the hydrogen hose and manifold

4. Installation of cold weather modifications
   a. Install upgraded heaters
   b. Remove existing bleed system
   c. Install new cold weather bleed system modifications
   d. Install cold weather exhaust modifications

5. Retrofit enclosure hardware for use with Independence 1000
   a. Replace rear door for fuel cell exhaust
   b. Remove unnecessary rack hardware
   c. Install additional necessary insulation

6. Removal of unnecessary testing hardware
   a. Removal of DC load bank
   b. Removal of enclosure batteries
   c. Rewiring to provide output power of enclosure directly to RTR DC bus
   d. Removal of DC load bank contactors and enclosure hardware

7. Install alarm wiring between fuel cell enclosure and FAA wireless alarm panel in RTR building

8. Provide updated drawing package to FAA

17.0 Additional Research/Analysis

The load bank used for Phase 1 testing consists of three resisters nominally rated at 0.7 ohm. The resisters are configured in parallel to provide the load increments at 24 to 27 Volts. The actual power dissipated at each increment depends on the voltage at each run and effective resistance of the load bank at its operating temperature. During each Phase 1 test run, the effective power spiked initially, and then settled down as the resisters heat up. At higher ambient temperatures, the power at the load bank near the end of the 3 kW increment can be almost 300 W below the initial maximum. An example of this initial spike and subsequent drop in power can be seen in Figure 9. This plot shows the 3 kW increment during the 4:00 PM run on June 5, 2003 when the indicated ambient temperature was over 38°C.

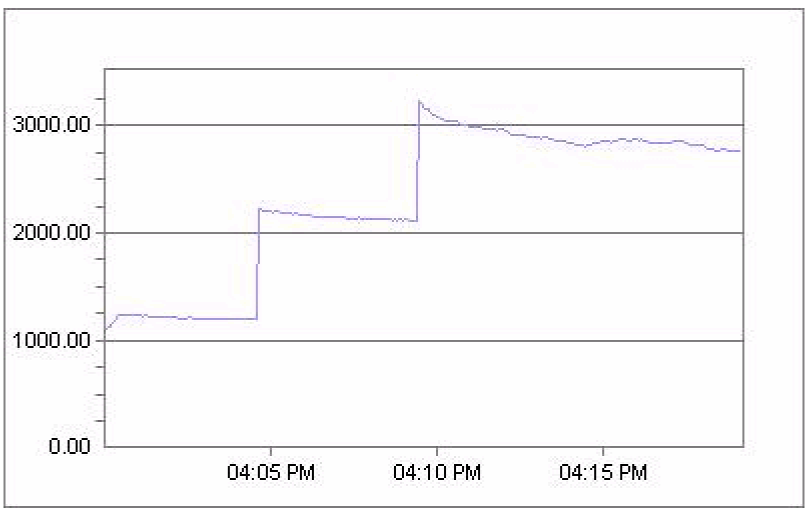


Figure 9. 4:00 PM Run, 6/5/2003

To verify that the drop in power at the load bank was a function of resister behavior and not a decrease in fuel cell performance during the run period, a constant load test using a 4 kW Dynaload was conducted on July 11, 2003. The test results are summarized in Figure 10 and show that the fuel cell system can maintain a constant net load at or above 3000 W.

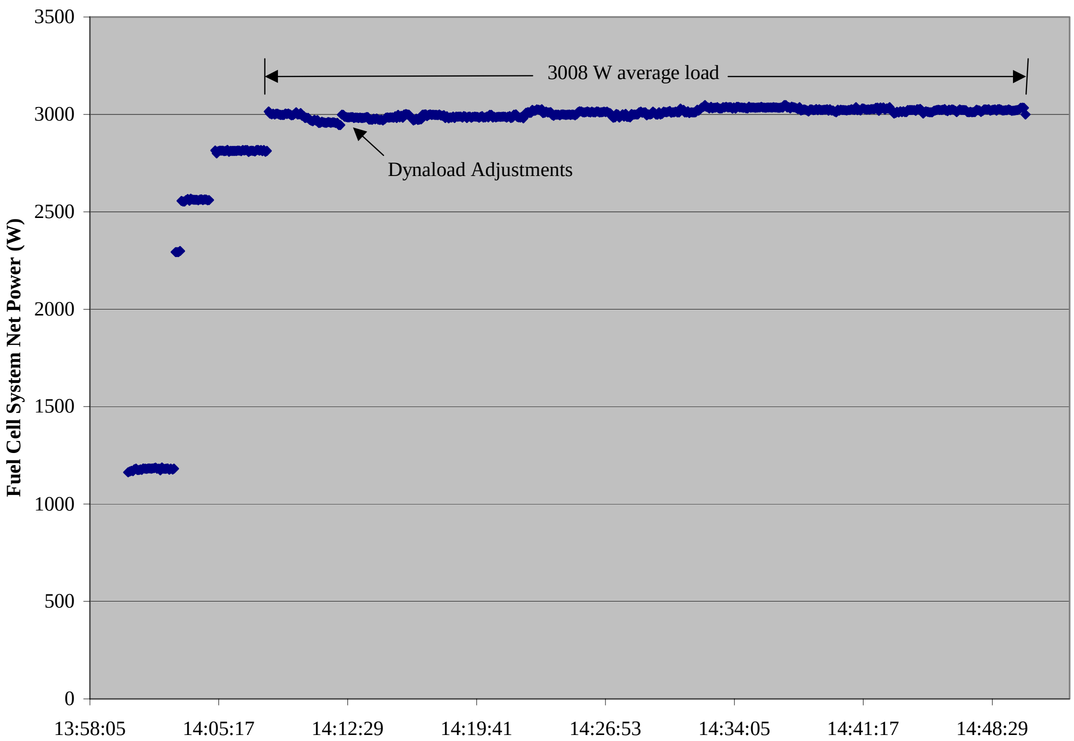


Figure 10. Constant Power Dynaload Test

Based on the results of the constant load test, the connecting lugs on the load bank resisters were adjusted to increase the current flow and average power delivered by the fuel cell system at the 3 kW set point. A trace of fuel cell system output power following these adjustments is shown in Figure 11.

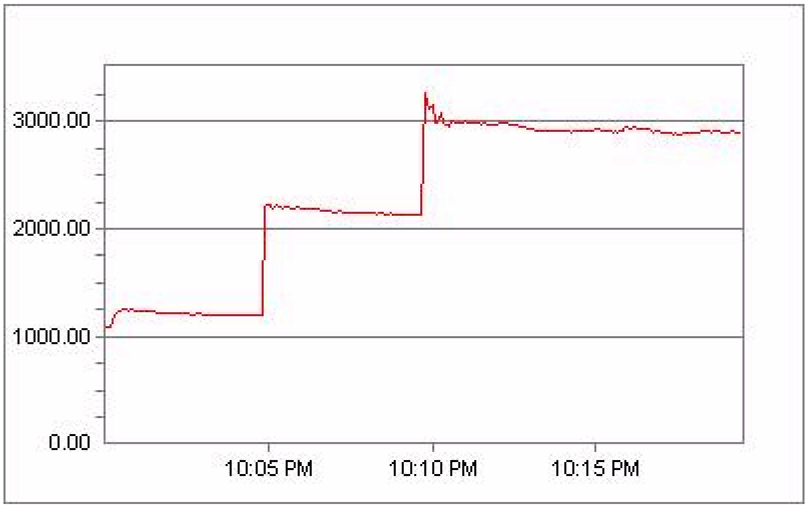


Figure 11. 10:00 PM Run, 8/7/2003

18.0 Conclusions/Summary

Through the end of the test program, the system was monitored for over 8800 hours and accumulated over 1106 successful starts for a total fuel cell run time of 418.9 hours. Total reliability (Actual Starts/Attempted Starts) for the entire test program was 99.4%. Total availability (Actual Run Time In Scheduled Period/Scheduled Run Time in Period) for the entire test program was 97.4%. The fuel cells themselves were very reliable throughout the 1 year demonstration program, presenting an effective presentation of ReliOn's modular, air cooled, self hydrating, planer technology. Total system reliability and availability factors of less than 100% were attributed to sub-components, which have since been replaced or redesigned.

Appendix

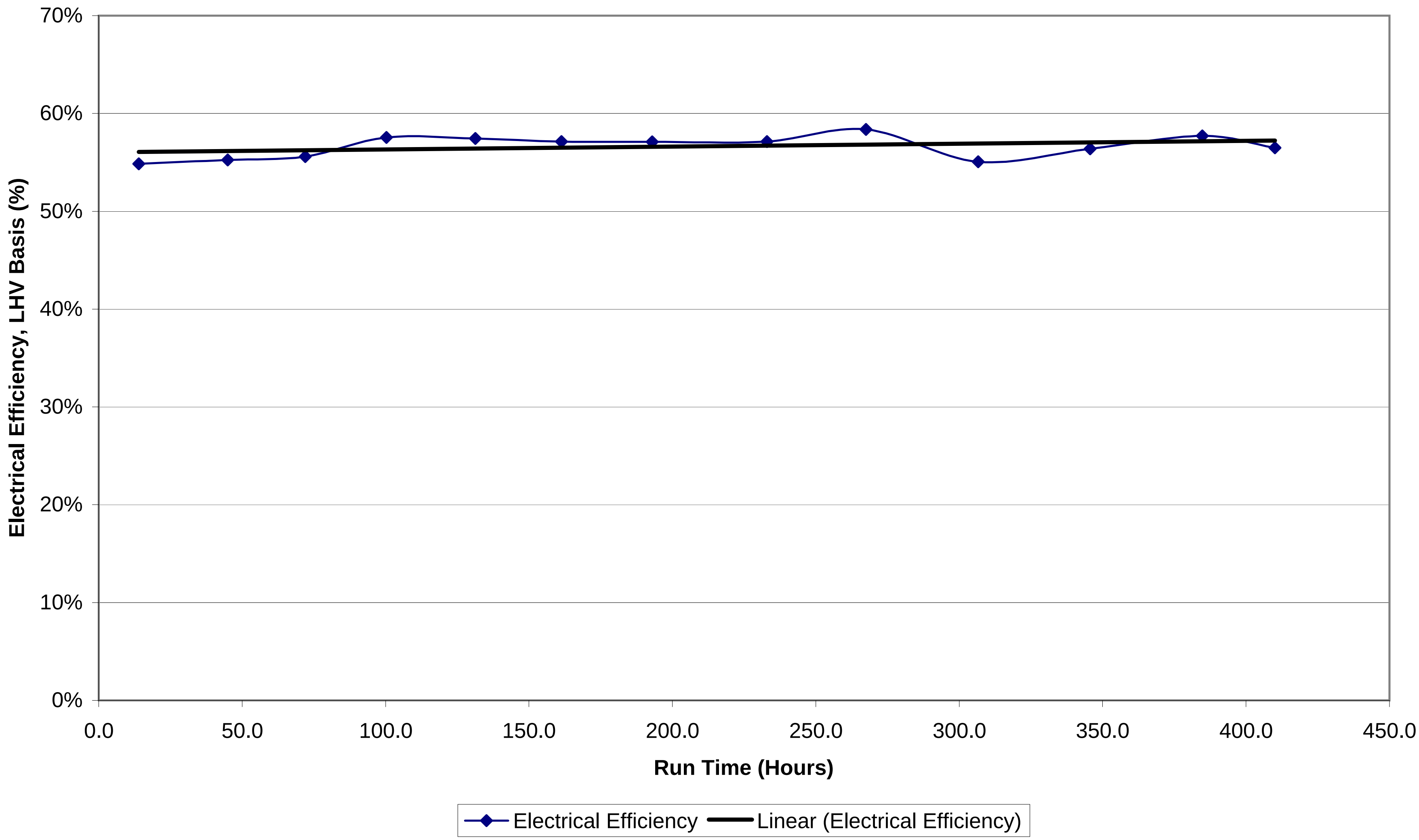
Appendix 1 – Monthly Performance Data
Appendix 2 – Maintenance Logs

Appendix 1a -- ReliOn PEM Fuel Cell Project
Totals for CERL II, McChord AFB.

Fuel Cell Site Grand Totals

Run Time (Hours)	358.8
Time in Period (Hours)	8808.3
Attempted Starts	1113
Actual Starts	1106
Reliability (%)	99.37%
Availability (%)	97.42%
Energy Produced (kWe-hrs AC)	834.2
Output Setting (kW)	3.00
Average Output (kW)	2.32
Capacity Factor (%)	3.16%
Fuel Usage, LHV (BTUs)	5.02E+06
Fuel Usage (SCF)	18844.1
Electrical Efficiency, LHV (%)	56.69%
Thermal Heat Recovery (BTUs)	0
Heat Recovery Rate (BTUs/hour)	0.00
Thermal Efficiency, LHV (%)	0.00%
Overall Efficiency, LHV (%)	56.69%
Number of Scheduled Outages	5
Scheduled Outage Hours	5.3
Number of Unscheduled Outages	6
Unscheduled Outage Hours	6.06

Appendix 1b
ReliOn McChord Electrical Efficiency



PEM Fuel Cell Performance Data

System Number:
Site Name: FAA RTR Site, McChord AFB
Fuel Type: Hydrogen
Lower Heating Value: 266.6 (Btu/scf)
Capacity kW 3

Commission Date: 17-Apr-03
Fuel Cell Type: Modular PEM
Maintenance Contractor: ReliOn
Local Residential Fuel Cost per therm: $0.71121+$5.50 per mon. **$/therm** (See Note *16 Below)
Local Residential Electricity Cost per kWhr: $.057568+$5.50 per mon. **$/kWhr** (See Note *18 Below)

Site Location(City,State): Tacoma, WA
Local Base Fuel Cost per therm: $.67760+$10.00 per mon. **$/therm** (See Note *17 Below)
Local Base Electricity Cost per kWhr: $.032063+$5.36/kW+$46.00 per mon. **$/kWhr** (See Note *19 Below)

Month	Total Time in Month (Hours)	Total Run Time During Month (Hours)	Run Time During Load Bank Test Periods (Hours)			Run Time During RTR Load Test Periods (Hours)			Total Run Time During Scheduled Test Periods	Attempted Starts	Actual Starts	Availability (%)	Reliability (%)	Energy Produced (kWe-hrs AC)	Plant Capacity (kW)	Average Output (kW)	Capacity Factor (%)	Fuel Usage, LHV (BTUs)	Fuel Usage (SCF)	Electrical Efficiency LHV Basis (%)	Thermal Heat Recovery (BTUs)	Heat Recovery Rate (BTUs/hour)	Thermal Efficiency LHV Basis (%)	Overall Efficiency LHV Basis (%)	Number of Scheduled Outages	Scheduled Outage Hours	Number of Unscheduled Outages	Unscheduled Outage Hours
			Scheduled	*Actual*	*Cumulative*	*Scheduled*	*Actual*	*Cumulative*	*Cumulative*			*1	*2	*insert produced energy*	*insert plant capacity*	*3	*4	*insert fuel consumption*	*insert fuel consumption*	*5	*insert heat recovery*	*6	*7	*8	*insert value*	*insert value*	*insert value*	*insert value*
April	312	14.0	14	14.0	14	0	0.0	0.0	14.0	42	42	100%	100%	33.373	3	2.38	3.57%	207748.6	779.25	54.84%	0	0	0.00%	54.84%	0	0	0	0
May [20]	744	31.0	31	31.0	45	0	0.0	0.0	45.0	93	93	100%	100%	73.432	3	2.37	3.29%	453748.4	1701.98	55.25%	0	0	0.00%	55.25%	0	0	0	0
June [21]	720	27.8	30	27.0	72	0	0.0	0.0	72.0	82	82	90.0%	100%	62.411	3	2.31	2.89%	383236.6	1437.50	55.60%	0	0	0.00%	55.60%	1	2.6	1	0.3
July [22]	744	33.6	31	28.3	100.3	0	0.0	0.0	100.3	83	83	91.4%	100%	59.684	3	2.11	2.67%	354048.1	1328.01	57.55%	0	0	0.00%	57.55%	4	2.7	0	0
August	744	31.8	31	31.0	131.3	0	0.0	0.0	131.3	93	93	100%	100%	72.015	3	2.32	3.23%	428031.0	1605.52	57.44%	0	0	0.00%	57.44%	0	0	0	0
September	720	30.0	30	30.0	161.3	0	0.0	0.0	161.3	90	90	100%	100%	66.836	3	2.23	3.09%	399506.7	1498.52	57.12%	0	0	0.00%	57.12%	0	0	0	0
October [23]	744	31.7	31	29.7	191.0	2	2.0	2.0	193.0	94	94	95.7%	100%	68.078	3	2.29	3.05%	407102.0	1527.01	57.09%	0	0	0.00%	57.09%	0	0	4	1.3
November	720	40.0	30	30.0	221.0	10	10.0	12.0	233.0	95	95	100%	100%	75.213	3	2.51	3.48%	449488.2	1686.00	57.13%	0	0	0.00%	57.13%	0	0	0	0
December [24]	744	34.5	31	28.5	249.5	8	6.1	18.0	267.5	97	90	91.9%	93%	67.522	3	2.37	3.03%	394986.8	1481.57	58.36%	0	0	0.00%	58.36%	0	0	1	4.5
January [25]	744	39.0	31	31.0	280.5	8	8.0	26.1	306.6	97	97	100%	100%	63.103	3	2.04	2.83%	391288.9	1467.70	55.06%	0	0	0.00%	55.06%	0	0	0	0
February	696	39.1	29	29.0	309.5	10	10.1	36.2	345.7	92	92	100%	100%	70.793	3	2.44	3.39%	428580.7	1607.58	56.39%	0	0	0.00%	56.39%	0	0	0	0
March [26]	744	39.4	31	31.0	340.5	8	8.1	44.2	384.7	97	97	100%	100%	75.088	3	2.42	3.36%	444171.9	1666.06	57.71%	0	0	0.00%	57.71%	0	0	0	0
April [27]	432.3	27.0	18.3	18.3	358.8	6	7.0	51.3	410.1	58	58	100%	100%	46.636	3	2.54	3.60%	281889.8	1057.35	56.48%	0	0	0.00%	56.48%	0	0	0	0

Running Totals	Time in Period (Hours)	Total Run Time During Month	Total Scheduled Run Time	Total Actual Run Time	Load Bank Test Cummulative Run Time	Total Scheduled Run Time	Total Actual Run Time	RTR Load Test Cummulative Run Time	Total Run Time During Scheduled Test Periods	Total Attempted Starts	Total Actual Starts	Total Availability (*9)	Total Reliability	Total Energy Produced	Average Output Setting	Total Average Output (*10)	Total Capacity Factor (*11)	Total Fuel Usage	Total Fuel Usage	Average Electrical Efficiency (*12)	Total Thermal Heat Recovery	Average Heat Recovery Rate (*13)	Average Thermal Efficiency (*14)	Average Overall Efficiency (*15)	Total Outages	Total Hours	Total Outages	Total Hours
	8808.3	418.9	368.3	358.8	358.8	52	51.3	51.3	410.1	1113	1106	97.4%	99.4%	834.187	3	2.32	3.16%	5.02E+06	18844.07	56.69%	0	0	0.00%	56.69%	5	5.3	6	6.1

Notes:

*1	Availability	=	Run Time / Time in Period
*2	Reliability	=	Actual Starts / Attempted Starts
*3	Average Output	=	Energy Produced / Run Time
*4	Capacity Factor	=	Average Output / Output Setting
*5	Electrical Efficiency	=	(Total Energy Produced * 3414 BTUs/kW-hr) / Total Fuel Usage
*6	Heat Recovery Rate	=	Thermal Heat Recovery / Run Time
*7	Thermal Efficiency	=	Thermal Heat Recovery / Total Fuel Usage
*8	Overall Efficiency	=	Electrical Efficiency + Thermal Efficiency
*9	Total Availability	=	Sum Total Run Time / Sum Total Hours in Period
*10	Total Average Output	=	Total Energy Produced / Total Run Time
*11	Total Capacity Factor	=	Total Energy Produced / (Total Capacity * Total Time in Period)
*12	Avg. Electrical Efficiency	=	(Total energy produced * 3414 BTUs/kWh) / Total Fuel Usage
*13	Avg. Heat Recovery Rate	=	Total Thermal Heat Recovery / Total Run Time
*14	Avg. Thermal Efficiency	=	Total Thermal Heat Recovery / Total Fuel Usage
*15	Avg. Overall Efficiency	=	Avg. Electrical Efficiency + Avg. Thermal Efficiency

*16 Puget Sound Energy Residential General Service, effective April 10, 2003
Delivery Charge = 26.113 ¢ per therm; Low Income Program = 0.405 ¢ per therm; Cost of Gas = 44.419 ¢ per therm; Conservation Charge = 0.184 ¢ per therm
Total Charge = 71.121 ¢ per therm
For more information see http://www.pse.com/account/rates/ratesgas.html

*17 Puget Sound Energy Commercial and Industrial General Service, effective April 10, 2003
Delivery Charge = 23.742 ¢ per therm; Low Income Program = 0.335 ¢ per therm; Cost of Gas = 43.499 ¢ per therm; Conservation Charge = 0.184 ¢ per therm
Total Charge = 67.760 ¢ per therm
For more information see http://www.pse.com/account/rates/ratesgas.html

*18 Tacoma Power Residential Service, Schedule A-1, effective March 31, 2003 for Tacoma and Pierce County
Energy Charge = $.030349 per kWh; Delivery Charge = $.027219 per kWh
Customer Charge = $5.50 per month for all but collectively metered apartments; $4.50 per month for collectively metered apartments
For more information see http://www.ci.tacoma.wa.us/power/Rates/residential.htm

*19 Tacoma Power Commercial Service, Schedule G General Service, effective March 31, 2003 for Tacoma and Pierce County
Energy Charge = $.032063 per kWh; Delivery Charge = $5.36 per kW based on billing demand for period
Customer Charge = $46.00 per month
For more information see http://www.ci.tacoma.wa.us/power/Rates/commercial.htm

*20 Includes three (3) runs on May 28 and May 29 when data uploader was offline.

*21 Does not include outage on June 28, 29, 30

*22 Does not include outages on July 1-3, July 11-12, and July 22. Includes three (3) runs for July 8 & July 9 when data uploader was offline.

*23 Three of Six fuel supply cylinders not properly connected. System operated on three cylinders only until exhausted during 10 PM run October 26. Special fuel delivery occurred on October 28. Fuel cells continued to start, but produced no power for three runs on October 27 and one run on October 28.

*24 Gas supply vendor missed regular delivery scheduled for December 24. Fuel supply exhausted during 4 AM run on December 28. Fuel cells started but shut down within 1 minute for 9 AM, 4 PM, and 10 PM runs on December 28, and 4 AM run on December 29. Fuel supplied replenished prior to 4 PM run on December 29.
Outdoor enclosure heater developed electric short during 10 PM run on December 29, tripping enclosure power breaker and leading to safety shutdown. Electric short also damaged data logging computer. Fuel cell system restarted for 4 PM and 10 PM runs on December 31. No data recorded until Temporary computer was installed on January 2. Energy Produced and Fuel Usage not recorded when data uploader was offline on Dec 31.

*25 Includes fuel cell system starts and run time when data uploader was offline. Energy Produced and Fuel Usage not recorded when data uploader was offline on Jan 1-5, 8-10, 15.

*26 Includes fuel cell system starts and run time when data uploader was offline during 4 PM run on March 8.

*27 Phase 1 and Phase 2 test programs shut down following 4 AM run on April 19, 2004

Appendix 1d -- ReliOn PEM Fuel Cell Project Data Summary for CERL II, McChord AFB.

Site Performance Matrix											
System No.	Total Run Hours	Scheduled Hours	Total Hours in Period	Attempted Starts	Actual Starts	Reliability (%)	Availability (%)	Capacity Factor (%)	Total Energy Produced (kWe-hrs AC)	Average Output (kW)	Electrical Efficiency LHV Basis (%)
	359	368	8808	1113	1106	99.4%	97.4%	3.2%	834	2.32	56.7%

Appendix 2a -- Maintenance Log for CERL II, McChord AFB.

Installation Date: 1/14/03

Maintenance Performed:

Date	Operator	Task
2/12/2003	Hager	Cartridge Serial # 3309 indicated failure, Unit 6, Cartridge slot #3. Brought back to Avista Labs for investigation
4/17/2003		Start Phase 1 Test Program
5/23/2003	Snow	Subrack 6 data not uploading from 10 PM run. Exit and re-launch CERL II Terminal Server.
5/26/2003	Snow	Subrack 6 data not uploading since 4 PM run on 5/26/03 (Memorial Day weekend). Exit and re-launch CERL II Terminal Server.
5/27/2003	Snow	Subrack 6 data not uploading from 4 AM run. Exit and re-launch CERL II Terminal Server.
5/27/2003	Snow	All subracks data not uploading from 4 PM run. Exit and re-launch CERL II Terminal Server.
5/28/2003	Snow	All subracks data not uploading from 4 AM run. Exit and re-launch CERL II Terminal Server.
5/28/2003	Snow	All subracks data not uploading from 4 PM run. Exit and re-launch CERL II Terminal Server.
5/28/2003	Snow	Exit and re-launch CERL II Terminal Server at 17.40.
5/29/2003	Snow	Discovered CERL II TS not connected at 9.45 AM.. Exit and re-set TS. 5-28-03 22:00 and 5-29-03 04:00 data will be lost but runs most likely OK.
6/6/2003	Snow	Replace all Gore cartridges in SR 4 and SR 6 with 3M/Centipede cartridges. Install Version 1.5M chip.
6/17/2003	Snow	Cartridge bus fuse blew on SR 4 on 6-15-2003. Replace with 35 Amp fuse.
6/26/2003	Snow	16.00 run: Approx. 4 min. into 2000 W segment, load fell back to ~1200 W. Load increased to ~2000 W briefly then fell back to ~1200 W. Appears to be related to load bank, not fuel cells.
6/27/2003	Snow	Intermittant load bank behavior continuing. Switching between 1, 2, and 3 kW during run.
6/28/2003	Snow	4.00 run: Load completely off-line. Shut down test due to safety concerns associated with failed load bank.
7/3/2003	Snow	Load bank and relays OK. Found low-level hydrogen signals with Tif detector. Suspect hydrogen leaks from solenoid valves or manifold on SR1. Replaced SR1 with spare unit. Replace several cartridges. Conduct extra full run at 14:00. Special test run using auto-start during 4:00 PM run period. Manually control load bank at 1 kW and 2 kW. Set PLC to ramp to 2 kW only for the weekend. Return on 7-6 to service system.
7/6/2003	Snow	System maintenance activities continued through 4:00 PM run. Load bank held at 1 kW during entire run.
7/8/2003		Data uploader offline for 4:00 PM & 10:00 PM runs
7/9/2003		Data uploader offline for 4:00 AM run
7/11/2003	Snow	Found leaking Gore cartridge in SR5. Hydrogen leaks causing H2 sensor trips. Replace all Gore cartridges in SR5. Install version 1.6r chip in SR5. Install air flow baffles in SR5. Removed spare unit and replaced original into SR1 space. SR1, SR4, SR5, and SR6 now equipped with 3M/Centipede cartridges. SR1, SR4, and SR5 have air flow baffles. SR1 and SR5 have version 1.6r chip. SR4 and SR6 have version 1.5m chip. Perform extra manual test runs. Perform Dynaload test on system. System maintains >3000 W for over 30 minutes. Determined that static resister load bank requires adjustment.
7/22/2003	Snow	Replace blown fuses on SR4 and SR6. Adjust tap location on R3 of load bank to reduce resistance and increase current at 3 kW setpoint. Placed clipboards with cylinder manifold pressure log in cylinder cabinets. H2 sensor maintenance activities continued through 4:00 PM run. No 4:00 PM run data.
8/7/2003	Snow	Replace all fuses with 50 Amp Fast Blow. Install version 1.7r chip in SR1, SR4, SR5, SR6. Replace SMC sensors in enclosure bays 1 & 2 with sensors calibrated to 2000 ppm. Set north hydrogen supply pressure to 48 psig. Set south hydrogen supply pressure to 56 psig. Replace 1 cartridge in SR5, 1 cartridge in SR6, 3 cartridges in SR 2.

Appendix 2a -- Maintenance Log for CERL II, McChord AFB.

Installation Date: 1/14/03

Maintenance Performed:

Date	Operator	Task
9/4/2003	Snow	Reset PLC clock to laptop clock to eliminate end-of-run alarms.
9/10/2003	Snow	Install 3M/Centipede cartridges in SR2 and SR3. Install version 1.7r chip in SR2 and SR3. Install air flow baffles in SR2 and SR3.
9/13/2003	Snow	Found leaking CPC fitting on bleed line in cabinet 1. Found unseated CPC fitting on bleed line in cabinet 2. Re-install SR3. Replaced 3 cracked cartridges. Replace 3 SMC sensors with Avista hydrogen sensors with 7500 ppm trip point.
10/26/2003		System low power. Appears to be loss of fuel. Asking AirGas supplier to check status of ball valves. AirGas reported gas cylinders empty.
12/28/2003		Out of fuel near end of 4 AM run. RTR run at 9 AM started but shut down. Also, load bank tests at 4 PM and 10 PM started but shut down.
12/29/2003		Out of fuel. Load bank test at 4 AM started but shut down. Airgas delivered 6 full cylinders following 4 AM run. 4 PM run OK.
12/29/2003		Heaters shorted prior to 10 PM run & tripped 20 Amp breaker in enclosure AC power distribution panel. Rectifier offline due to breaker trip. Battery voltage was at 21 V at beginning of run and insufficient to start all fuel cells. PLC continued to run load bank until batteries depleted.
12/30/2003		Depleted batteries did not provide sufficient power to run PLC and start 4 AM, 4 PM, or 10 PM fuel cell runs.
12/31/2003	Snow	Found heater shorted & 20 Amp breaker tripped in enclosure AC power distribution panel. Found 10 Amp fuse (F9) to rectifier blown, although not sure if fuse F9 tripped during diagnostic evaluation. One of two reaction air fans not operating on SR1. SR1 giving low power. Replace SR1.
1/2/2004	Snow	Install Foam cartridges in SR3. Install version 1.9r (24 V, no H2) firmware
2/10/2004		Subracks 1 and 2 shut down during 10 PM, and 4 AM runs during cold temperatures. Faulty fuse holder for subrack heaters in cabinet 1 popped open disconnecting power to fuel cell heaters.
2/11/2004	Hager	Reconnected heater fuse in cabinet 1. Tested all heaters to ensure operation. Replaced 1 faulty cartridge and three cracked cartridges. Verified all cartridge serial numbers. Inpected hydrogen enclosure and piping for leaks. Ran system test.
3/10/2004		SR5 not operating from 4 AM run.
3/15/2004	Snow	Found corroded fuse and fuse holder in SR5. Fuse tested OK. Cleaned fuse holders in all units. Installed new fuse in SR5. Ran two 20 minute tests.

Appendix 2b -- Cartridge Log for CERL II, McChord AFB.

Subrack 1	"Original"		April 17, 2003		June 6, 2003		July 3, 2003		July 12, 2003		August 7, 2003		September 10, 2003		September 13, 2003		October 15, 2003		December 9, 2003		December 31, 2003		January 2, 2004		January 8, 2004		February 12, 2004		March 9, 2004		March 15, 2004	
Slot	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**
Slot 1	3393	Gore	3882	3M	3882	3M/Centi	3882	3M/Centi [d]	4018	3M/Centi	4018	3M/Centi	4018	3M/Centi	4018	3M/Centi	4018	3M/Centi	4018	3M/Centi	4018	3M/Centi	4018	3M/Centi	4018	3M/Centi	4018	3M/Centi	4018	3M/Centi	4018	3M/Centi
Slot 2	3335	Gore	3808	3M	3808	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi	3964	3M/Centi
Slot 3	3321		3809	3M	3809	3M/Centi [d]	3841	3M/Centi	4017	3M/Centi	4017	3M/Centi	4017	3M/Centi	4017	3M/Centi	4017	3M/Centi	4017	3M/Centi	4017	3M/Centi	4017	3M/Centi	4017	3M/Centi	3711	3M/Centi	3711	3M/Centi	3711	3M/Centi
Slot 4	3585	3M	3744	3M	3744	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi	4013	3M/Centi
Slot 5	3597	3M	3750	3M	3750	3M/Centi	3750	3M/Centi	4016	3M/Centi	4016	3M/Centi	4016	3M/Centi	3944	3M/Centi	3944	3M/Centi	3944	3M/Centi	3944	3M/Centi	3944	3M/Centi	3944	3M/Centi	3944	3M/Centi	3944	3M/Centi	3944	3M/Centi
Slot 6	3285	Gore	3585	3M	3585	3M/Centi	4054	3M/Centi	4054	3M/Centi	4054	3M/Centi	4054	3M/Centi [b,f]	4016	3M/Centi	4081	3M/Centi	3841	3M/Centi [d]	3879	3M/Centi	3879	3M/Centi	3879	3M/Centi	4017	3M/Centi	4017	3M/Centi	4017	3M/Centi
Slot 7	3378	Gore	3742	3M	3742	3M/Centi	3841	3M/Centi	3841	3M/Centi	3841	3M/Centi	3841	3M/Centi	3841	3M/Centi	3841	3M/Centi	4081	3M/Centi	4081	3M/Centi	4081	3M/Centi	4081	3M/Centi	3879	3M/Centi	3879	3M/Centi	3879	3M/Centi
Slot 8	3381	Gore	3782	3M	3782	3M/Centi	4023	3M/Centi	4023	3M/Centi	4023	3M/Centi	4023	3M/Centi	4023	3M/Centi	4023	3M/Centi	4023	3M/Centi	4023	3M/Centi	4023	3M/Centi	4023	3M/Centi	3706	3M/Centi	3706	3M/Centi	3706	3M/Centi
Slot 9	3397	Gore	3743	3M	3743	3M/Centi [d]	4016	3M/Centi	4009	3M/Centi	4009	3M/Centi	4009	3M/Centi	4009	3M/Centi	4009	3M/Centi	4009	3M/Centi	4009	3M/Centi	4009	3M/Centi	4009	3M/Centi	4009	3M/Centi	4009	3M/Centi	4009	3M/Centi
Slot 10	3301	Gore	3785	3M	3785	3M/Centi	3607	3M/Centi	3607	3M/Centi	3607	3M/Centi	3607	3M/Centi [d]	4020	3M/Centi	4020	3M/Centi	4020	3M/Centi	4020	3M/Centi	4020	3M/Centi	4020	3M/Centi	4020	3M/Centi	4020	3M/Centi	4020	3M/Centi

Subrack 2	"Original"		April 17, 2003		June 6, 2003		July 3, 2003		July 12, 2003		August 7, 2003		September 10, 2003		September 13, 2003		October 15, 2003		December 9, 2003		December 31, 2003		January 2, 2004		January 8, 2004		February 12, 2004		March 9, 2004		March 15, 2004	
Slot	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**
Slot 1	3279	Gore	3279	Gore	3279	Gore	3279	Gore	3279	Gore	3279	Gore	3727	3M/Centi	3727	3M/Centi	3727	3M/Centi	3727	3M/Centi	3727	3M/Centi	3727	3M/Centi	3727	3M/Centi	3668	3M/Centi	3668	3M/Centi	3668	3M/Centi
Slot 2	3297	Gore	3297	Gore	3297	Gore	3297	Gore	3297	Gore [d]	3327	Gore	4051	3M/Centi	4051	3M/Centi	4051	3M/Centi	4051	3M/Centi	4051	3M/Centi	4051	3M/Centi	4051	3M/Centi	3692	3M/Centi	3692	3M/Centi	3692	3M/Centi
Slot 3	3362	Gore	3362	Gore	3362	Gore	3362	Gore	3362	Gore	3362	Gore	4069	3M/Centi [d]	4056	3M/Centi	4056	3M/Centi	4056	3M/Centi [d]	3562	3M/Centi	3562	3M/Centi	3562	3M/Centi	3400	3M/Centi	3400	3M/Centi	3400	3M/Centi
Slot 4	3432	Gore	3432	Gore	3432	Gore	3432	Gore	3432	Gore	3432	Gore	4071	3M/Centi	4071	3M/Centi	4071	3M/Centi	4071	3M/Centi	4071	3M/Centi	4071	3M/Centi	4071	3M/Centi	4071	3M/Centi	3607	3M/Centi	3607	3M/Centi
Slot 5	3357	Gore	3357	Gore	3357	Gore	3357	Gore	3357	Gore [d]	3276	Gore	4074	3M/Centi	4074	3M/Centi	4074	3M/Centi	4074	3M/Centi	4074	3M/Centi	4074	3M/Centi [b]	3868	3M/Centi	3868	3M/Centi	3868	3M/Centi	3868	3M/Centi
Slot 6	3573		3300	Gore	3300	Gore	3300	Gore	3300	Gore	3300	Gore	4075	3M/Centi	4075	3M/Centi	4075	3M/Centi	4075	3M/Centi	4075	3M/Centi	4075	3M/Centi	4075	3M/Centi	3682	3M/Centi	3682	3M/Centi	3682	3M/Centi
Slot 7			3335	Gore	3335	Gore	3335	Gore	3335	Gore	3335	Gore	4077	3M/Centi	4077	3M/Centi	3750	3M/Centi	3750	3M/Centi	3750	3M/Centi	3750	3M/Centi	3750	3M/Centi	3693	3M/Centi	3693	3M/Centi	3693	3M/Centi
Slot 8	3287	Gore	3287	Gore	3287	Gore	3287	Gore	3287	Gore	3287	Gore	4081	3M/Centi	3743	3M/Centi	3743	3M/Centi	3743	3M/Centi	3743	3M/Centi	3743	3M/Centi	3743	3M/Centi	3743	3M/Centi	3743	3M/Centi	3856	3M/Centi
Slot 9	3256	Gore	3256	Gore	3256	Gore	3256	Gore	3256	Gore	3256	Gore	4083	3M/Centi	4083	3M/Centi	4083	3M/Centi	4083	3M/Centi	4083	3M/Centi	4083	3M/Centi	4083	3M/Centi	4083	3M/Centi	4083	3M/Centi	4083	3M/Centi
Slot 10	3383	Gore	3383	Gore	3383	Gore	3383	Gore	3383	Gore [d]	3385	Gore	4085	3M/Centi	4085	3M/Centi	4085	3M/Centi	4085	3M/Centi	4085	3M/Centi	4085	3M/Centi	4085	3M/Centi	4085	3M/Centi	4085	3M/Centi	4085	3M/Centi

Subrack 3	"Original"		April 17, 2003		June 6, 2003		July 3, 2003		July 12, 2003		August 7, 2003		September 10, 2003		September 13, 2003		October 15, 2003		December 9, 2003		December 31, 2003		January 2, 2004		January 8, 2004		February 12, 2004		March 9, 2004		March 15, 2004	
Slot	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**
Slot 1	3379	Gore	3379	Gore	3379	Gore	3379	Gore	3319	Gore	3319	Gore	4073	3M/Centi	4086	3M/Centi	4086	3M/Centi	4086	3M/Centi	4086	3M/Centi	4166	3M/Foam	4166	3M/Foam	4166	3M/Foam	4166	3M/Foam	4166	3M/Foam
Slot 2	3324		3324	Gore	3324	Gore	3324	Gore	3324	Gore	3324	Gore	4072	3M/Centi	4076	3M/Centi	4076	3M/Centi	4076	3M/Centi	4076	3M/Centi	4130	3M/Foam	4130	3M/Foam	4130	3M/Foam	4130	3M/Foam	4130	3M/Foam
Slot 3	3342		3342	Gore	3342	Gore	3342	Gore	3342	Gore	3342	Gore	4086	3M/Centi	3878	3M/Centi	3878	3M/Centi	4047	3M/Centi	4047	3M/Centi	4126	3M/Foam	4126	3M/Foam	4126	3M/Foam	4126	3M/Foam	4126	3M/Foam
Slot 4	3217		3217	Gore	3217	Gore	3217	Gore [b]	3395	Gore	3395	Gore	4020	3M/Centi	4084	3M/Centi	4084	3M/Centi	4084	3M/Centi	4084	3M/Centi	4114	3M/Foam	4114	3M/Foam	4114	3M/Foam	4114	3M/Foam	4114	3M/Foam
Slot 5	3395		3395	Gore	3395	Gore	3395	Gore	3301	Gore	3301	Gore	3573	3M/Centi	3820	3M/Centi	3820	3M/Centi	3820	3M/Centi	3820	3M/Centi	4122	3M/Foam	4122	3M/Foam	4122	3M/Foam	4122	3M/Foam	4122	3M/Foam
Slot 6	3394		3394	Gore	3394	Gore	3394	Gore	3394	Gore	3394	Gore	3944	3M/Centi	3874	3M/Centi	3874	3M/Centi	3874	3M/Centi	3874	3M/Centi	4118	3M/Foam	4118	3M/Foam	4118	3M/Foam	4118	3M/Foam	4118	3M/Foam
Slot 7	3338		3338	Gore	3338	Gore	3338	Gore	3338	Gore	3338	Gore	3820	3M/Centi	3584	3M/Centi	3731	3M/Centi	4072	3M/Centi	4072	3M/Centi	4123	3M/Foam	4123	3M/Foam	4123	3M/Foam	4123	3M/Foam	4123	3M/Foam
Slot 8	3286		3286	Gore	3286	Gore	3286	Gore	3286	Gore	3286	Gore	4076	3M/Centi	4072	3M/Centi	4072	3M/Centi	3819	3M/Centi [d]	4077	3M/Centi	4127	3M/Foam	4127	3M/Foam	4127	3M/Foam	4127	3M/Foam	4127	3M/Foam
Slot 9	3282		3282	Gore	3282	Gore	3282	Gore	3282	Gore	3282	Gore	3584	3M/Centi	4073	3M/Centi	4073	3M/Centi	4073	3M/Centi	4073	3M/Centi	4121	3M/Foam	4121	3M/Foam	4121	3M/Foam	4121	3M/Foam	4121	3M/Foam
Slot 10	3396		3396	Gore	3396	Gore	3396	Gore	3396	Gore	3396	Gore	4084	3M/Centi	4000	3M/Centi	4000	3M/Centi	4000	3M/Centi	4000	3M/Centi	4169	3M/Foam	4169	3M/Foam	4169	3M/Foam	4169	3M/Foam	4169	3M/Foam

Subrack 4	"Original"		April 17, 2003		June 6, 2003		July 3, 2003		July 12, 2003		August 7, 2003		September 10, 2003		September 13, 2003		October 15, 2003		December 9, 2003		December 31, 2003		January 2, 2004		January 8, 2004		February 12, 2004		March 9, 2004		March 15, 2004	
Slot	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**
Slot 1	3318	Gore	3318	Gore	3717	3M/Centi	3717	3M/Centi	3717	3M/Centi	3717	3M/Centi	3717	3M/Centi	3717	3M/Centi	3717	3M/Centi	3722	3M/Centi [b]	3857	3M/Centi	3857	3M/Centi	3857	3M/Centi	3857	3M/Centi	3857	3M/Centi	3857	3M/Centi
Slot 2	3345	Gore	3345	Gore	3877	3M/Centi	3877	3M/Centi	3877	3M/Centi	3877	3M/Centi	3877	3M/Centi	3877	3M/Centi	3877	3M/Centi	3877	3M/Centi	3877	3M/Centi	3877	3M/Centi	3877	3M/Centi	3905	3M/Centi	3905	3M/Centi	3905	3M/Centi
Slot 3	3320	Gore	3320	Gore	3722	3M/Centi	3722	3M/Centi	3722	3M/Centi	3722	3M/Centi	3722	3M/Centi	3722	3M/Centi	3722	3M/Centi	3717	3M/Centi	3717	3M/Centi	3810	3M/Centi	3810	3M/Centi	3935	3M/Centi	3935	3M/Centi	3935	3M/Centi
Slot 4	3361	Gore	3361	Gore	3842	3M/Centi	3842	3M/Centi	3842	3M/Centi	3842	3M/Centi	3842	3M/Centi	3842	3M/Centi	3842	3M/Centi	3842	3M/Centi	3842	3M/Centi	3863	3M/Centi	3855	3M/Centi	3955	3M/Centi	3844	3M/Centi	3844	3M/Centi
Slot 5	3382	Gore	3382	Gore	3810	3M/Centi	3810	3M/Centi	3810	3M/Centi	3810	3M/Centi	3810	3M/Centi	3810	3M/Centi	3810	3M/Centi	3810	3M/Centi	3810	3M/Centi	3717	3M/Centi	4076	3M/Centi	4076	3M/Centi	3955	3M/Centi	3955	3M/Centi
Slot 6	3305	Gore	3305	Gore	3825	3M/Centi	3825	3M/Centi	3825	3M/Centi	3825	3M/Centi	3825	3M/Centi	3825	3M/Centi	3825	3M/Centi	3825	3M/Centi	3861	3M/Centi	3861	3M/Centi	3861	3M/Centi	3877	3M/Centi	3877	3M/Centi	3877	3M/Centi
Slot 7	3283	Gore	3283	Gore	3845	3M/Centi [d]	3744	3M/Centi	3744	3M/Centi	3744	3M/Centi	3744	3M/Centi	3744	3M/Centi	3744	3M/Centi	3744	3M/Centi	3744	3M/Centi	3744	3M/Centi	3744	3M/Centi	3861	3M/Centi	3861	3M/Centi	3861	3M/Centi
Slot 8	3386	Gore	3386	Gore	3858	3M/Centi	3858	3M/Centi	3858	3M/Centi	3858	3M/Centi	3858	3M/Centi	3858	3M/Centi	3858	3M/Centi	3858	3M/Centi	3858	3M/Centi	3858	3M/Centi	3858	3M/Centi	4023	3M/Centi	4023	3M/Centi	4023	3M/Centi
Slot 9	3261	Gore	3261	Gore	3861	3M/Centi	3861	3M/Centi	3861	3M/Centi	3861	3M/Centi	3861	3M/Centi	3861	3M/Centi	3861	3M/Centi	3861	3M/Centi	3825	3M/Centi [d]	3874	3M/Centi	3874	3M/Centi	3874	3M/Centi	3874	3M/Centi	3874	3M/Centi
Slot 10	3260	Gore	3260	Gore	3863	3M/Centi	3863	3M/Centi	3863	3M/Centi	3863	3M/Centi	3863	3M/Centi	3863	3M/Centi	3863	3M/Centi	3863	3M/Centi	3863	3M/Centi	3842	3M/Centi	3842	3M/Centi	3475	3M/Centi	3475	3M/Centi	3475	3M/Centi

Subrack 5	"Original"		April 17, 2003		June 6, 2003		July 3, 2003		July 12, 2003		August 7, 2003		September 10, 2003		September 13, 2003		October 15, 2003		December 9, 2003		December 31, 2003		January 2, 2004		January 8, 2004		February 12, 2004		March 9, 2004		March 15, 2004	
Slot	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**
Slot 1	3760		3381	Gore	3381	Gore	3381	Gore	3867	3M/Centi	3867	3M/Centi	3867	3M/Centi	3867	3M/Centi	3867	3M/Centi	3867	3M/Centi	3867	3M/Centi	3867	3M/Centi	3867	3M/Centi	3867	3M/Centi	3867	3M/Centi	3867	3M/Centi
Slot 2	3253	Gore	3253	Gore	3253	Gore	3253	Gore	3848	3M/Centi	3848	3M/Centi	3848	3M/Centi	3848	3M/Centi	3848	3M/Centi	3848	3M/Centi	3848	3M/Centi	3848	3M/Centi	3848	3M/Centi	3590	3M/Centi	3590	3M/Centi	3590	3M/Centi
Slot 3	3385	Gore	3385	Gore	3385	Gore	3385	Gore	4025	3M/Centi	4025	3M/Centi	4025	3M/Centi	4025	3M/Centi	4025	3M/Centi	4025	3M/Centi	4025	3M/Centi	4025	3M/Centi	4025	3M/Centi	4025	3M/Centi	4025	3M/Centi	4025	3M/Centi
Slot 4	3327	Gore	3327	Gore	3327	Gore	3327	Gore	3742	3M/Centi [e]	3742	3M/Centi [e]	3742	3M/Centi [e]	3742	3M/Centi [e]	3742	3M/Centi [e]	3742	3M/Centi [e]	3742	3M/Centi [e]	3742	3M/Centi [e]	3742	3M/Centi [e]	3742	3M/Centi [e]	3665	3M/Centi	3665	3M/Centi
Slot 5	3281	Gore	3281	Gore	3397	Gore	3397	Gore [a]	3808	3M/Centi [e]	3808	3M/Centi [e]	3808	3M/Centi [e]	3808	3M/Centi [e]	3808	3M/Centi [e]	3811	3M/Centi [e]	3811	3M/Centi [e, d]	4072	3M/Centi	4072	3M/Centi	4072	3M/Centi	4072	3M/Centi	4072	3M/Centi
Slot 6	3346	Gore	3346	Gore	3346	Gore	3346	Gore	3782	3M/Centi [e]	3782	3M/Centi [e]	3782	3M/Centi [e]	3782	3M/Centi [e]	3752	3M/Centi	3752	3M/Centi	3752	3M/Centi	3752	3M/Centi	3752	3M/Centi	3728	3M/Centi	3728	3M/Centi	3728	3M/Centi
Slot 7	3337	Gore	3337	Gore	3337	Gore	3337	Gore	3809	3M/Centi [d, e]	3778	3M/Centi	3778	3M/Centi	3778	3M/Centi	3778	3M/Centi	3817	3M/Centi	3817	3M/Centi	3817	3M/Centi	3817	3M/Centi	3817	3M/Centi	3817	3M/Centi	3817	3M/Centi
Slot 8	3307	Gore	3307	Gore	3307	Gore [d]	3307	Gore [c]	3785	3M/Centi [e]	3785	3M/Centi [e]	3785	3M/Centi [e]	3785	3M/Centi [e]	3785	3M/Centi [e]	3785	3M/Centi [e]	3785	3M/Centi [e]	3785	3M/Centi [e]	3785	3M/Centi [e]	4042	3M/Centi	4042	3M/Centi	4042	3M/Centi
Slot 9	3339	Gore	3339	Gore	3339	Gore	3339	Gore	4001	3M/Centi	4001	3M/Centi	4001	3M/Centi	4001	3M/Centi	4001	3M/Centi	4001	3M/Centi	4001	3M/Centi	4001	3M/Centi	4001	3M/Centi	3565	3M/Centi	3846	3M/Centi	3846	3M/Centi
Slot 10	3276	Gore	3276	Gore	3276	Gore	3276	Gore	3585	3M/Centi [e]	3585	3M/Centi [e]	3585	3M/Centi [e]	3585	3M/Centi [e]	3585	3M/Centi [e]	3585	3M/Centi [e]	3585	3M/Centi [e]	3585	3M/Centi [e]	3585	3M/Centi [e]	4001	3M/Centi	4001	3M/Centi	4001	3M/Centi

Subrack 6	"Original"		April 17, 2003		June 6, 2003		July 3, 2003		July 12, 2003		August 7, 2003		September 10, 2003		September 13, 2003		October 15, 2003		December 9, 2003		December 31, 2003		January 2, 2004		January 8, 2004		February 12, 2004		March 9, 2004		March 15, 2004	
Slot	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**	**S/N**	**Membrane**
Slot 1	3343	Gore	3343	Gore	3716	3M/Centi	3716	3M/Centi	3716	3M/Centi	3716	3M/Centi	3716	3M/Centi	3716	3M/Centi	3716	3M/Centi	3716	3M/Centi	3716	3M/Centi	3716	3M/Centi	3716	3M/Centi	3716	3M/Centi	3893	3M/Centi	3893	3M/Centi
Slot 2	3322	Gore	3322	Gore	3707	3M/Centi	3707	3M/Centi	3707	3M/Centi	3707	3M/Centi	3707	3M/Centi	3707	3M/Centi	3707	3M/Centi	3707	3M/Centi	3707	3M/Centi	3707	3M/Centi	3707	3M/Centi	3843	3M/Centi	3843	3M/Centi	3843	3M/Centi
Slot 3	3275	Gore	3275	Gore	3851	3M/Centi	3851	3M/Centi	3851	3M/Centi [d]	4002	3M/Centi	4002	3M/Centi	4002	3M/Centi	4002	3M/Centi	4002	3M/Centi	4002	3M/Centi	4002	3M/Centi	4002	3M/Centi	4002	3M/Centi	4002	3M/Centi	4002	3M/Centi
Slot 4	3314	Gore	3314	Gore	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi	3726	3M/Centi
Slot 5	3374	Gore	3374	Gore	3715	3M/Centi	3715	3M/Centi	3715	3M/Centi	3715	3M/Centi	3715	3M/Centi	3715	3M/Centi	3715	3M/Centi	3715	3M/Centi	3715	3M/Centi	3715	3M/Centi	3715	3M/Centi	3902	3M/Centi	3902	3M/Centi	3902	3M/Centi
Slot 6	3387	Gore	3387	Gore	3844	3M/Centi [d]	3750	3M/Centi	3750	3M/Centi	3750	3M/Centi	3750	3M/Centi	3750	3M/Centi	4077	3M/Centi	3809	3M/Centi	3809	3M/Centi	3809	3M/Centi	3809	3M/Centi	3946	3M/Centi	3946	3M/Centi	3946	3M/Centi
Slot 7	3384	Gore	3384	Gore	3725	3M/Centi	3725	3M/Centi	3725	3M/Centi	3725	3M/Centi	3725	3M/Centi	3725	3M/Centi	3725	3M/Centi	4048	3M/Centi	4048	3M/Centi [d]	4000	3M/Centi	4000	3M/Centi	3721	3M/Centi	3721	3M/Centi	3721	3M/Centi
Slot 8	3262	Gore	3262	Gore	3860	3M/Centi	3860	3M/Centi	3860	3M/Centi	3860	3M/Centi	3860	3M/Centi	3860	3M/Centi	3860	3M/Centi	3860	3M/Centi	3860	3M/Centi [d]	4073	3M/Centi	4073	3M/Centi	4073	3M/Centi	4073	3M/Centi	4073	3M/Centi
Slot 9	3259	Gore	3259	Gore	3850	3M/Centi	3850	3M/Centi	3850	3M/Centi	3850	3M/Centi	3850	3M/Centi [d]	3845	3M/Centi	3845	3M/Centi	3845	3M/Centi	3845	3M/Centi	3845	3M/Centi	3845	3M/Centi	3730	3M/Centi	3730	3M/Centi	3730	3M/Centi
Slot 10	3311	Gore	3311	Gore	3862	3M/Centi	3862	3M/Centi	3862	3M/Centi	3862	3M/Centi	3862	3M/Centi	3862	3M/Centi	3862	3M/Centi	3862	3M/Centi	3862	3M/Centi	3862	3M/Centi	3862	3M/Centi	3880	3M/Centi	3880	3M/Centi	3880	3M/Centi

Cartridge Removed

Notes: New Cartridge

[a] Discovered large leak on next service call. Cartridge replaced at next service call.

[b] Repeated cartridge trips. Cartridge replaced at next service call.

[c] Loose cover screws. Re-torque cover screws and place in back-up cartridge inventory.

[d] Cover cracked. Replaced at next service call.

[e] Cartridges running since April 17 in SR1. Suspected leaking, but tested and passed at Avista Labs.

[f] Lab tests revealed high impedence to LL MEA. Suspect cell reversal damage due to membrane flooding or water blockage of gas flow passages.